

MEDIUM ACCESS CONTROL PROTOCOL  
FOR DATA COMMUNICATIONS

**Field of the Invention**

This invention relates to the field of data communications, and to methods and apparatus to implement a Medium Access Control (MAC) protocol therefor. The invention has particular (but not exclusive) application in wireless communications environments such as  $\mu$ -wave, mm-wave or infra-red. The term "data communications" is to be understood in its broadest sense to include data *per se*, and forms such as voice and video.

**Background of the Invention**

For discussion purposes, reference will be made to wireless MAC protocols, however it should be understood that the invention is equally applicable to cabled (ie. wire and optical fibre) and wireless data communications alike.

A protocol generally is a set of agreed conventions (methodology) for handling the exchange of information between communication/processing "elements".

In a wireless medium, the capacity to accommodate multiple users seeking access to the medium must take into account fundamental limitations of bandwidth. For any wireless data communications system there is a finite data carrying capacity, and this capacity must be shared between users on an appropriate basis to satisfy the user's requirements. A number of MAC protocols have been devised for this purpose. Such protocols variously attempt to satisfy the objective of providing users with access to the full medium during times of low load demand, and fair access to the medium during times of high load demand. Furthermore, it may be desirable to guarantee a user the ability to transmit or receive a burst of data on demand regardless of other user load demands.

Usually, users requesting access to a wireless medium will require low reception delays and high throughput. Where wireless data communication services are supplied on a subscription basis, the subscribing users negotiate certain guaranteed performance requirements that have to be met in order for the service provider to retain that subscriber's loyalty.

Known protocols fall broadly within four classes: fixed access, random access, guaranteed access, and hybrid protocols.

The fixed access category includes those MAC protocols where each station is allocated a fixed proportion of the available bandwidth. This category includes time division multiple access (TDMA), frequency division multiple access (FDMA) and code division multiple access (CDMA) protocols. The main problem with fixed access protocols is that they are not flexible enough to efficiently meet the dynamic bandwidth

A random access protocol is only statistical in its nature and therefore its performance is never guaranteed. There are many examples of random access protocols including those based on ALOHA, Carrier Sense Multiple Access (CSMA) and collision resolution. Random access protocols can generally be characterised by the following properties. At low aggregate loads, a random access protocol usually provides low delay. At high loads, contention will limit throughput and increase delay. Scheduling of transmission by a random access protocol also is difficult due to the lack of guarantees about access to the wireless medium. Similarly, prioritised access to the wireless medium cannot be ensured. ALOHA protocols also tend to ignore collisions, whereas CSMA protocols tend to try and avoid collisions or limit the length of collisions.

Most practical, implementable wireless MAC protocols are designed as a hybrid of two or more protocols from the previously described categories. This allows a wireless MAC protocol to be tailored more easily to provide a range of services given a particular set of wireless physical layer properties. Hybrid protocols are mostly based on the idea of contention on the wireless medium followed by a reservation that holds the wireless medium for a single station without contention.

A variation of R-ALOHA, Packet Reservation Multiple Access (PRMA), solves these problems for voice traffic. PRMA supports periodic data units (voice traffic) and random data units (data traffic). Only periodic data units can reserve the same slot in future frames. Random data units always use slotted ALOHA access. Problems similar to those experienced for R-ALOHA are avoided in two ways. Firstly, periodic data units are buffered only for a limited period before they are transmitted or

discarded, thus reducing the load during congestion. Secondly, stations must give up reservations between talk spurts. PRMA is thus very dependent on the properties of speech for effective operation. Another example of this physical layer dependence is that the frame rate in PRMA is tied to the speech rate.

- 5 In a published paper entitled "A Dynamic packet-switching system for Satellite Broadcast Channels", (ICC'75, San Francisco, June 1975) the author Binder describes a TDMA based satellite communication scheme where all stations own a channel (or channels) in a frame structure. The frame may have more channels than those owned by stations. All stations receive each transmitted packet via the satellite. Each packet  
10 header includes a reservation for the station's queued packets. Stations which do not have a current reservation will have their owned channel used for reservation access. Each station allocates reservation requests on a round-robin basis. A station with new packets to transmit may regain its owned channel by causing a collision. In the next frame all stations will consider the channel reserved by its owner which can then make  
15 a reservation request. A master station generates frame markers and transmits the reservation state. This is used by new stations and stations which have lost a packet and hence the reservation sequence.

- There is a problem here, however, with packets received with errors. If the packet contained reservations which were processed by other stations, then the  
20 receiving station cannot use the reservation scheme for the rest of the frame. This is hard to distinguish from intentional collisions intended to free an owned channel. In addition, a station must receive what it transmits to detect a purposeful collision.

- The Motorola ALTAIR™ system uses a reservation protocol with time multiplexed request and data channels in a slotted frame. The start of the frame  
25 contains request slots in which user modules (UM) make requests to a central control module (CM) using slotted ALOHA access with an adaptive transmission probability. The end of the frame contains a series of grant slots, which specify the allocation of data slots in the next frame, and a series of management slots. The middle part of the frame contains data slots from the CM to the UMs and allocated data slots from the  
30 UMs to the CM. Control information is distributed through blocks at the start and end of a frame with intervening data slots. The mobile station needs to track where it is in this structure and it will lose considerable efficiency if it has a problem receiving a critical block.

- An access request is made by competitive ALOHA in the start control block  
35 with no feedback until the end of frame control block. Access slots occur in the midst of a potentially long series of user slots. Any failure to track the user slot sequence will affect a station's throughput and the throughput of any other station it collides with. Bandwidth must be consumed to provide guard time between these slots to allow for variation in clock speed between stations.

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DFWMAC also includes a second mode of operation, known as a point coordination function, which effectively provides a synchronous data unit service. In

this mode, a central hub station divides the bandwidth into a frame consisting of a contention free period and a contention period. During the contention free period, a hub station polls mobile stations on a polling list. The hub station starts a contention free period by sending the first poll at a high priority. The reservation mechanism is  
5 entirely unsophisticated: 'send a message during the contention period'. There are no methods to respond to bursty traffic or to attempt to make efficient use of the medium.

U.S. Patent No. 4,970,720, Hiroshi Esaki assigned to Toshiba K K, entitled "A Packet Communication Exchanging Apparatus" describes an even simpler CSMA/CA scheme for wired and wireless LANs. Here a station causes a collision to  
10 obtain access to the medium by forcing active stations to delay access attempts.

## Disclosure of the Invention

The present invention is directed to overcoming or at least ameliorating one or more of the disadvantages in the prior art. Embodiments described herein specify a medium access control protocol that provides mechanisms to make efficient use of the available wireless transmission capacity while supporting the operation of synchronous and asynchronous communications, with guaranteed performance according to negotiated parameters, between a mobile station and a hub station.

Therefore, the invention broadly discloses a method for controlling  
20 communications access between a hub and a plurality of distributed stations over a  
medium, the method comprising the steps of:

(a) allocating a plurality of channels for data communications between the stations and the hub, the number of channels being at least equal to the number of stations, and each station owning at least one channel, each channel being varyingly in one of an empty-, a reserved-, or an owner-state, and whereby:

(i) the empty-state provides a channel to which any station can have access;

(ii) the reserved-state provides a channel to which a station having made a reservation with the hub, but not owning the channel, can have access; and

30 (iii) the owner-state provides a channel to which only the owning station  
has access; and

(b) re-allocating the respective state and/or the number of channels over time on the basis of each station's data requirements.

35 The invention further discloses a method for controlling communications access between a hub and a plurality of mobile stations via a plurality of channels providing data access therebetween, there being at least as many channels as mobile stations, and the channels being varyingly in one of an empty-, a reserved-, or an owner-state, and whereby:

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(i) the empty-state provides a channel to which any station can have access;

(ii) the reserved-state provides a channel to which a station having made a reservation with the hub, but not owning the channel, can have access; and

5 (iii) the owner-state provides a channel to which only the owning station has access;

the method comprising the steps of re-allocating the respective state and/or the number of channels over time on the basis of each station's data requirements.

The invention yet further discloses a communications system having controlled data access to a medium, the system comprising:

10 a hub having transceiving means for communication via the medium and data processing means;

a plurality of distributed stations, each having transceiving means for communication with the hub via the medium and data processing means;

15 and wherein said data processing means of the hub and the stations co-operate to allocate a plurality of channels for data communications between the stations and the hub, the number of channels being at least equal to the number of stations, and each station owning at least one channel, each channel being varyingly in one of an empty-, a reserved-, or an owner-state, and wherein:

20 (i) the empty-state provides a channel to which any station can have access,

(ii) the reserved-state provides a channel to which a station having made a reservation with the hub, but not owning the channel, can have access, and

(iii) the owner-state provides a channel to which only the owning station

25 has access, and co-operate to re-allocate the respective state and/or the number of channels over time on the basis of each station's data requirements.

The invention yet further discloses a hub for a communications system, operable to have controlled data access to a medium in co-operation with a plurality of distributed stations, the hub comprising:

transceiving means for communications via the medium; and

data processing means coupled to the transceiving means;

35 and wherein said data processing means of the hub is operable to allocate a plurality of channels for data traffic between the stations and the hub, the number of channels being at least equal to the number of stations, each channel being varyingly in one of an empty-, a reserved-, or an owner-state, and wherein:

(i) the empty-state provides a channel to which any station can have access,

- (ii) the reserved-state provides a channel to which a station having made a reservation with the hub, but not owning the channel, can have access, and
- (iii) the owner-state provides a channel to which only the owning station has access,
- 5 and further operable to re-allocate the respective state and/or the number of channels over time on the basis of each station's data requirements.

The invention yet further discloses a wireless local area network having a medium access protocol to control access, the network comprising:

- a hub having transceiving means for communication via free space paths and  
10 data processing means;

a plurality of distributed stations, each having transceiving means for communication with the hub via free space paths and data processing means;

- and wherein said data processing means of the hub and the stations co-operate to allocate a plurality of channels for data traffic between the stations and the hub, the  
15 number of channels being at least equal to the number of stations, and each station owning at least one channel, each channel being varyingly in one of an empty-, a reserved-, or an owner-state, and wherein:

- (i) the empty-state provides a channel to which any station can have access,
- 20 (ii) the reserved-state provides a channel to which a station having made a reservation with the hub, but not owning the channel, can have access, and
- (iii) the owner-state provides a channel to which only the owning station has access,
- and co-operate to re-allocate the respective state and/or the number of channels over  
25 time on the basis of each station's data requirements.

- Embodiments of the invention have the benefit of simultaneously: (a) guaranteeing a minimum access to the network transmission capacity for each mobile station according to negotiated channel parameters, (b) unreserved capacity can be used by other mobile stations, thereby providing such mobile stations with capacity in excess  
30 of a guaranteed minimum, and obtained independent of hub control and without requiring additional complexity in the mobile unit, and (c) provides parameters to maximise the probability of successful transmission by one mobile station in situations of competitive access to a slot, including registration slots and empty slots.

- One characteristic of the medium access protocol is that it is demand oriented  
35 rather than a requesting type known in the prior art.

#### Brief Description of the Drawings

Embodiments of the invention now will be described with reference to the accompanying drawings, in which:

Fig. 2 is a schematic block diagram of a wireless LAN system in another embodiment;

**Fig. 4 is a schematic block diagram of a hub station;**

**Figs. 6 to 9 show the structures of transmission in a wireless cell;**

**Figs. 11a-11c show state diagrams for a mobile station; and**

## 15 Description of Preferred Embodiments and Best Modes

Fig. 1 shows a simplified form of a wireless system 5, in which a single transceiving hub station 8 facilitates data communications between a number of distributed transceiving mobile stations 9. The mobile stations 9 can be mobile within a cell (not shown) controlled by the hub station 8. The hub station 8 acts to coordinate bidirectional data communications between the mobile stations 9, in the example shown, between stations M1 and M3.

35 Fig. 3 shows a block diagram of a wired network system 17, upon which a protocol embodying the invention also can be implemented. As previously noted, the invention is not limited to wireless environments. A number of terminals (T1-T5) 9' are in cabled connection 13' with a hub station (H1). The cabled connection 13' has the characteristic that the hub station H1 communicates with the terminals 9' using



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Software implementing a MAC protocol embodying the invention resides in the timing and control elements 28,38 of a hub station 8 and mobile station 9 respectively.

- 5 (a) a garbled data unit which cannot be interpreted; this is called "collision" and no "capture" has occurred, or
- (b) a correct data unit where the mobile with the strongest signal has swamped the others; this is "capture".

The description of the data link procedures will proceed with reference to the system shown in either Figs. 1 or 2, and particularly wireless communications between a hub station 8 and a mobile station 9.

Slots are organised into channels. A channel is the set of either down-link (hub to mobile) or up-link (mobile to hub) slots, respectively addressed, to or owned by the same mobile station. Each up-link channel, if allocated to a mobile station, is said to be owned by it.

When there are no mobile stations registered, the hub station data units relate principally to registration. Unregistered mobile stations use a modified ALOHA protocol to deliver registration requests to the hub station. These requests include the station's unique MAC address, called the station-id. This is included in the registration confirmation response from the hub station to avoid 'capture' related problems.

35           The hub station transmits data units to a specific mobile by setting the station-id of the mobile in the header of the data unit.

The hub station uses a scheduling algorithm to determine which channel will be allocated for a down-link and for the following up-link. Mobiles use a modified R-ALOHA protocol, along with their internal state, to determine use of the up-link.

5 transmitted was successfully received by the hub station.

Following registration, a mobile station can request that the hub station adjust  
10 the parameters controlling its traffic service characteristics.

The protocol data units (PDU) are constituted differently for the up-link and down-link. Fig. 8 shows the protocol data unit fields for the down-link, while Fig. 9 shows the protocol data unit fields for the up-link. Tables 1A & 1B describe these fields.

Field	Description
dest-id	Identifier of the destination for the payload
source-id	Identifier of the source of the payload.
type	An identifier for a down link data unit format, additionally distinguishing between data and management payloads.
chan-id	Channel identifier for the following up-link. This is in the range 0 to (max_number_allocated_channels - 1) or registration_chan_id (a known number outside that range)
chan-state	The state of the following up-link slot: empty, owner or reserved (Note: the registration channel is always in empty-state)
up-link_result	The result of last up-link transmission as ack or nack.
ack-id	If up-link_result = ack, ack-id is the identifier of the successful source mobile station else unused.
est-num	For the next up-link slot: <ul style="list-style-type: none"> <li>For registration: estimated number of registering mobile stations</li> <li>For data: estimated number of active mobile stations</li> </ul>
sleep-num	The duration of sleep following next up-link slot.
payload	<ul style="list-style-type: none"> <li>For a data transmission: fixed length data, eg 4 x 53 bytes.</li> <li>For a management transmission: management data units including beacon, management request and management response.</li> </ul>
crc	Data unit integrity check.

Table 1A - Hub station protocol data unit fields

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Field	Description
dest-id	Identifier of the destination for the payload
source-id	Identifier of the source of the payload.
type	An identifier for an up link data unit format, additionally distinguishing between data and management payloads.
flow-rq	Flow request for this channel
contend-rq	Request to be counted as a mobile station competing for ALOHA slots.
payload	<ul style="list-style-type: none"> <li>For a data channel: fixed length data, eg 4 x 53 bytes</li> <li>For a management transmission: management data units including registration request, management request and management response.</li> </ul>
crc	Data unit integrity check.

### Table 1B - Mobile station protocol data unit fields

## HUB STATION OPERATION

5           Operation of the hub station 8 in the wireless cell now will be described with reference to Fig. 10, which is a state machine relating to the timing of the alternating hub-originated and mobile-originated transmission sequence. The process state 40 includes the handling of any received data units from the mobile stations, the processing of acknowledgments, and the generation of the next down link data unit. The transition  
10       from the process state 40 to the transmit state 41 is controlled by a slot tick 43 generated by a clock (not shown). Upon completion of a slot transmission, the hub moves to the receive state 42. The hub returns to the process state 40 upon reception of a data unit from a mobile station or after a specified time period.

The transfer of data units out of the wireless cell, ie. to and from a backbone  
15 network, may be accomplished asynchronously from the handling of data units to and  
from the mobiles, and is governed by the protocol on the backbone network.

### Hub Cycle

The hub station includes the channel identifier of the next up-link slot in the header part of each down-link slot. Although a channel may be used by any mobile station, priority is given to the mobile station that owns the channel. The sequencing of channels is determined by the 'scheduler' process in the hub station taking into account the requirements of each mobile station, including the required service parameters and sleep requirements. Every mobile station registered in a cell is allocated at least one channel. In this way, all mobile stations can be guaranteed some access to the network.

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The hub station scheduler is initially set for no registered mobiles. In this state, all down-link and up-link slots may be allocated to the management channel, with the intention that they be used for registration.

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Registration up-link result		Change to estimated # of registrants	Next down-link ack/nack
Mobile Tx	Collision		
no	no	0 (see Note)	nack
yes	yes	+2	nack
yes	no	-1	ack

**Note:** The absence of any activity for a pre-defined long period of time should result in the estimate being set to zero.

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The hub station always transmits in down-link slots to mobile stations in a cell. The down-link payload may contain data originating from within the cell, from elsewhere in the network, or from the hub station itself.

Each up-link channel is defined to be in one of three states (empty, reserved or owner). The hub station stores the state of each channel and transmits the state of the next channel (along with other control fields) to the mobile stations in the header field of each down-link slot. The three channel states are defined as follows:

If a data channel is in the empty-state, any mobile station with queued data units is allowed to contend for access to it using a slotted ALOHA protocol. Mobile stations may make reservations for the channel in future frames according to a modified R-ALOHA protocol.

25 If a channel is in the reserved-state, the mobile station that has reserved the channel may transmit a data unit. However, the owner of the channel may sometimes use it regardless of the mobile station that has reserved the channel.

If a channel is in the owner-state, only the mobile station that owns the channel  
30 may use it to transmit a data unit. Channels allocated to a mobile station with  
negotiated channel parameters are called "provisioned" and remain in the owner-state.  
Thus the owner of a channel has guaranteed access.

At the end of each up-link slot the hub station changes the channel state according to the State Table shown in Table 3, and selects the next channel according to a scheduling algorithm.

Provisioned Channel	Up-link State <sup>4</sup>		Up-link Result <sup>4</sup>			Update	Next	Send
	Channel State	Mobile is Owner	Mobile Tx	Collision	Flow Request	est-num	Channel State	ack / nack
no	empty or reserved <sup>1</sup>	X	yes	yes	X	no	owner	nack
no	" <sup>2</sup>	no	yes	no	res	yes	reserved	ack
no	"	yes	yes	no	own	yes	owner	ack
no	" <sup>3</sup>	X	yes	no	no	yes	empty	ack
no	"	X	no	no	no	no	empty	nack
no	owner	yes	yes	no	own	yes	owner	ack
no	"	X	yes	no	no	yes	empty	ack
no	"	X	no	X	X	no	empty	nack
yes	"	yes	yes	no	X	yes	owner	ack
yes	"	yes	yes	yes	X	no	owner	nack
yes	"	yes	no	no	X	no	owner	nack

Where  $X = \text{don't care}$ .

Note: 1. Owner pre-emption.

## 2. Reservation.

### 3. End of flow.

4. Other states represent protocol error states which may be due to hub station failure, mobile failure or a denial of service attack. The appropriate response may include a hub station restart.

**Table 3 - Up-link data channel state transitions**

The columns under "Provisioned Channel", "Up-link State" and "Up-link Result" describe the type of the channel, the state of the channel and the result of the latest reception on that channel. The "Update est-num" column indicates whether to use the up-link contend-rq field to update the estimated number of contending mobiles (ie. est-num). In the right hand columns the new state for the channel is given and the "Send ack/nack" column shows what should be sent in the next down-link slot in response to the mobile's data unit.

The hub station is required to acknowledge and to count mobile stations whenever their contend-rq signal indicates that they will be contending for ALOHA slots. The hub station transmits a mobile station estimate in a field in the MAC header part of every down-link.



If a mobile station is to be counted by the hub station then it makes a contend-request in the header part of an up-link slot at the same time it attempts to send a data unit.

- 5 The hub must exchange management data units with mobile stations for control tasks which may include registration completion (which might involve security), channel parameter negotiation and sleep control. The channel parameter negotiation may alternatively be delivered by standard signalling procedures.

#### Hub Station Scheduler

- 10 The hub station may enter into contracts with mobile stations to provide certain channel parameters in which it will allocate a portion of the available capacity for the use of that mobile station. The protocol described herein supports guaranteed channel parameter contracts. The hub station supports these contracts with a scheduler that is fair and does not degrade the performance of any existing contracts. The acceptance of  
15 a contract requires the allocation of hub station resources up to, but not exceeding, the hub station's total (bandwidth) capacity.

#### Hub Sleep Scheduling

- 20 The protocol described herein supports a mode of operation in which the mobile enters a low-power mode that does not require it to listen to every down-link slot. For a mobile indicating a sleep requirement, the slot scheduler can allocate owned slots during the period when the mobile is awake.

#### MOBILE STATION OPERATION

- 25 A mobile station's operation will be described with reference to Fig. 11.

#### Mobile cycle

- The activity of the mobile station is determined in response to messages received from the hub station. Fig 11a shows that a mobile station operates in three  
30 states 'init' 50, 'registration' 51, and 'data' 52. The state 'registration' 51, entered after initialisation or as a result of losing contact with the hub, is expanded in Fig 11b. An unregistered mobile station is in the 'registration-listen' state 53 in which it waits for the hub to issue a registration slot. The mobile enters the 'request-registration' state 54 if it attempts to register. The 'data' state 52 is expanded in Fig 11c. A mobile  
35 receives down-link slots from the hub in 'data-receive' state 55. Down-link data units are processed in state 'data-process' 56. Depending on the outcome of the processing, the mobile either exits the 'data' state 52 or enters one of three states: the 'data-transmit' state 57 in which it transmits a data unit in the next up-link slot; the 'data-sleep' state 58 in which it conserves power; or the 'data-receive' state 55.

### Mobile Registration

In the 'registration' state 51 shown in Fig. 11a, the mobile operates in accordance with the Registration State Table shown in Table 4 below. The objective of the procedures described by the Registration State Table is to competitively deliver a message to the hub station. The hub station provides an estimate of the number of mobiles it believes are attempting to register. A mobile uses the inverse of this number to set the probability of transmitting its registration request. This is used to increase the probability of a successful registration transmission by delaying, or spreading in time, registration requests of the contending mobile stations.

Channel identifier	Mobile Tx Probability	Result		Next Mobile State
		Mobile Tx	Hub response	
registration_chan_id	$1/(\text{est-num} + 1)$	yes	nack	registration
registration_chan_id	$1/(\text{est-num} + 1)$	yes	ack	data
registration_chan_id	$1/(\text{est-num} + 1)$	no	X	registration
other	0	no	X	registration

**Table 4 - Mobile registration state table**

In Table 4, 'Channel identifier' is the 'chan-id' field in the previous down-link protocol data unit. 'Mobile Tx probability' is used by the mobile station to set the probability that it will attempt to access the channel. The next two columns describe the result of the mobile access attempt: 'Mobile Tx' states whether or not the mobile did attempt to access the channel, and 'Hub response' is the response by the hub station that appears in the down-link slot immediately following the registration attempt and defines whether the registration attempt has succeeded.

### Mobile Channel Parameter Request

The mobile station requests channel characteristics consistent with the hub station's scheduling algorithm. The method of delivery of this request to the hub station depends on the networking environment, but can be accomplished through management processing.

### Mobile Data Transmission

The following section further describes the operations carried out in the 'data' state 52 of Fig. 11a and its expanded form in Fig. 11c.

The header in an up-link data unit may include a flow request (see Table 1B) that is set by a Mobile station to reserve exclusive access to the channel. The logic to

[illegible]

**all other cases**

**= in addition**

**= don't care**

### Table 5 - Mobile data state table

In Table 5, the 'Current state' columns give the state following receipt of a down-link data unit. The 'Transmission decision' columns indicate whether the mobile station should transmit, what flow requests should be made and consequent action. The 'Tx Probability' specifies the probability that the mobile station will transmit. In three cases the transmission probability is determined from the hub station's estimate of the number of mobiles contending for ALOHA access. To compress the table, the Flow Record Update' columns are separated according to whether a transmission was made (first 3 columns) or not (4th column). The first 3 columns specify how the mobile station should update its flow record for each of three possible acknowledgment responses in the next down-link data unit. The action here modifies the flow status of the channel just used. Entry 'no' means that there is no owner or reserve flow and 'res' or 'own' means that 'reserve flow' or 'owner flow' respectively is recorded.

Table 5 also specifies that the mobile station should count errored data units, indicated in the table by 'channel state' = 'unknown'. This number can be used to decide when the link has become unreliable and remedial action needs to be taken, ie. a return from 'data' state 52 to the 'registration' state 51 shown in Fig. 11a.

Also, whenever a mobile transmits it sets its contend-rq field according to Table 6 to assist the hub station in its determination of the number of mobiles contending for empty slots.

Queue length	Contend-Rq
> 1	yes
≤ 1	no

**Table 6 - Mobile station Contend-Rq Generation**

**Owner Flow Requests:**

An owner-flow request is a flow request made by a mobile station for a channel that it owns. On receipt of an owner flow request the hub station changes the channel state to owner, meaning only the owner of the channel is allowed access to the channel. This facility allows the owner of a channel to dynamically create a contention free TDMA-like channel for its own use. Even if the hub station does not receive the slot containing the owner-flow request correctly, due to a collision or other error, the request is still successful because the hub station assumes that the owner of the channel has caused the collision to regain access to the channel. This state will not persist unnecessarily as the owner must request retention of owner-state in successive slots.

An owner-flow request must receive a positive acknowledgment with the owner ack-id to be considered successful. A mobile station that makes an owner-flow request marks the channel as an owner flow and increments "Flows", a counter in each

$$\text{FlowRequestAllowed} = (\text{QueueLength} > \text{Flows} + 1).$$

**ReleaseRequired = (FlowCounter = 0).**

Negotiated access by stations can be scheduled without contention and with  
35 delays agreed upon. The remaining traffic involves contended access to the network,  
including traffic subject to statistical multiplexing. This contended traffic has been the  
subject of simulation.

Two independent methods were used to perform the simulation. The result shown here were derived from a software implementation of the protocol using the C programming language. In this simulation the hub and mobile stations, were each implemented as a thread, where all communications among them were restricted to information in the packet exchanges illustrated in Figs. 11. The traffic used in the simulations was generated using Poisson statistics. The base simulation unit was a time-slot, instead of absolute time in seconds, as a result the performance illustrated is valid for arbitrary slot sizes.

These simulation results were verified using a commercial simulation package, called OPNET, supplied by MIL 3, Inc, 3400 International Drive, Washington D.C. 20008.

Figs. 12-15 variously have as an indices 'Offered Load' vs 'Throughput', where a value of 1 indicates the whole part of the bandwidth available for non-guaranteed traffic and 'Delay' vs 'Throughput'. The channel may have scheduling agreements for, say, 90% of its capacity, with the remaining 10% being subject to contention.

Figs. 12 and 13 show the situation of ten mobile stations competing with equal probability for network access. The hub does round-robin scheduling of the ten slots owned by the stations.

The throughput plot shows that the protocol is converting the Offered Load directly to throughput over almost the entire range. Also shown on Fig. 12 is additional protocol-related traffic required to obtain competitive access. This region between "data" and "data+collision" shows increasing activity as the probability of slotted ALOHA type collisions increases as load increases, then a progressive reduction as the protocol's behaviour becomes more TDMA like. The delay remains better than that achieved in pure TDMA, conventionally taken to be  $1 + (\text{no. slots} / 2)$ , in this case 6 slots, until the offered load reaches 0.3. Then it increases as collisions cause delayed access. However this still stays quite low until the offered load approaches 0.9. At this point mean delay grows rapidly because a TDMA mode of operation is not uniformly established and where collision is still being used to obtain access queue length (hence delay) will increase.

Figs. 14 and 15 relate to a simulation where there are again ten stations being offered their owner slots on a round-robin basis.

However, one station (causing "heavy" traffic) is generating 90% of the system's Offered Load while the other nine stations (causing "light" traffic) evenly share the remaining 10% of the Offered Load. Note that there are no traffic agreements here. The Offered Loads are still for the contended part of the system bandwidth only.



The system Throughput directly matches the Offered Load up to an Offered Load of around near 0.8. The "heavy" traffic station will attempt to use all the slots it requires while "light" traffic stations will increasingly need to collide to temporarily reserve their owned slots to deliver a packet. The region representing collisions shows this behaviour. As the system load becomes high, the "light" station will need to use nearer and nearer to 10% of the channel. To obtain this they will consume an increasing part of the bandwidth in collisions. So, after reaching a peak, throughput will decline as collisions become more likely. As the decision to transmit is probabilistic, even the (data + collision Throughput) cannot reach 1.

At the same time, the "heavy" station will have increasing difficulty emptying its queue and its delay increases sharply. On the other hand, the "light" stations can regain their owned channel and dispatch their packets before another arrives. Figs. 13 and 15 show very good Delay performance.

This demonstrates excellent fairness, in that the heavy user did not prevent  
15 stations with modest requirements from using the network.

Embodiments of the invention provide advantages (or avoid disadvantages) over the prior art MAC hybrid protocols discussed earlier. In relation to R-ALOHA, the present MAC protocol attempts to reserve multiple slots depending on how many data units have been buffered. However, it does not retain reserved slots beyond its immediate need to use them or beyond the specified consecutive number of accesses. Also, in comparison with R-ALOHA there is an improvement in performance by stations owning channels which can be preempted on demand, where the demand includes collision of transmission, and also by structuring uplink and downlink slots so as to provide immediate feedback to a previous transmission attempt. In relation to the PRMA protocol, the present protocol, in contrast, does not distinguish between "voice" and "other" traffic, in which case there is no reliance on characteristics of voice traffic, such as freedom to discard data units, or relatively fixed frame rates. The technique of obtaining access to reserved slots has been enhanced by the concept of "owner channel" which may be rapidly forced into a reserved-state rather than waiting for an ALOHA access to succeed.

Turning now to the ALTAIR™ system, for the present protocol control information is distributed in time and each slot access is controlled by the previous slot header and acknowledged by the following slot header. Failure to read one of the control messages will result in the loss of only one slot access, which is a small impact. 35 Further, the present protocol uses a number of schemes to generate access, including the guaranteed reservation, thereby obviating the need for complex feedback. Finally, the present protocol allows mobile stations to respond directly to hub station messages, in that there is no requirement to determine when a granted slot number occurs. There

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A yet further application is for wireless systems in homes or offices for the distribution of entertainment services and data between a set-top box provided by a service provider to a number of televisions, and/or computers and associated peripherals.

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